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CARBON MONOXIDE HAZARDS FROM HOUSE HEATERS BURNING NATURAL GAS

BY

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CONTENTS.

Page.

Introduction........ 1

Acknowledgments........ 2

Combustion products from natural gas........ 2

  Carbon monoxide........ 3

    Properties........ 3

    Toxicity........ 3

    Symptoms of carbon monoxide poisoning........ 4

  Combustion of natural gas........ 4

    Composition........ 4

  Air required for combustion........ 5

  Methods of introducing air........ 5

Method of making tests........ 6

Types of heaters tested........ 7

  Type 1. Lava-tip, yellow-flame heater........ 7

    Discussion of results........ 9

  Type 2. Metal-inclosed blue-flame heater with adjustable primary-air inlet 10

    Discussion of results........ 10

  Type 3. Asbestos-back yellow-blue flame heater, with a fixed primary air supply and a metal and mica guard in front........ 12

    Discussion of results........ 13

  Type 4. Cylindrical, blue-flame bathroom heater, protected on outside by perforated metal shield........ 16

    Discussion of results........ 16

  Type 5. Radiant nonluminous-flame heater with adjustable orifice for gas and fixed primary air supply........ 17

    Discussion of results........ 18

  Type 6. Blue-flame radiator heater whose combustion products pass through an absorbent before liberation........ 19

    Discussion of results........ 19

Percentage of oxygen present at the moment the flames of natural-gas heaters are extinguished........ 20

Time required to extinguish the natural-gas flame of a heater in a closed room.. 22

Maximum accumulation of carbon monoxide in a ventilated room........ 23

  Carbon monoxide percentages at different air-change rates........ 23

  Discussion of results........ 25

Are "gas fumes" an indication of carbon monoxide?........ 25

Conclusions........ 28

Publications on the utilization of natural gas........ 30

TABLES.

TABLE 1. Results of tests of a lava-tip, yellow-flame heater having 21 lava tips with opening one-tenth inch diameter........ 8

2. Results of tests of a metal-inclosed blue-flame heater, with shutter-type primary-air inlet........ 11

3. Results of tests of an asbestos-back, yellow-blue flame heater, having fixed primary air mixer and a mica and metal guard in front of flame 13

Page.
TABLE 4. Results of tests of cylindrical, blue-flame bathroom heater protected on outside by perforated shield 15
5. Results of tests of radiant-type nonluminous heater having adjustable orifice for gas and fixed primary air supply 17
6. Results of tests of a blue-flame radiator heater 21
7. Oxygen content of atmosphere when flames of different heaters were extinguished, per cent by volume 22
8. Time required before flame is extinguished 22
9. Percentage of carbon monoxide that would accumulate in a room of 1,000 cubic feet capacity, ventilated at varying air-change rates an hour, from different types of heaters burned continuously for one and for five hours 24

ILLUSTRATIONS.

PLATE I. Interior of room in which house heaters were tested 6
FIGURE 1. Lava-tip, yellow-flame heater 7
2. Metal-inclosed type, blue-flame heater with adjustable primary inlet 10
3. Asbestos-back heater having fixed primary air supply and a metal and mica guard in front of flame 12
4. Cylindrical, blue-flame bathroom heater, protected on outside by perforated metal shield 16
5. Radiant-type nonluminous heater 17
6. Radiator-type heater with attachment for removing "noxious gases" 20
7. Curves showing percentage of CO that would accumulate at varying air-change rates in a room having a capacity of 1,000 cubic feet. 26

CARBON MONOXIDE HAZARDS FROM HOUSE HEATERS BURNING NATURAL GAS.

By G. W. Jones, L. B. Berger, and W. F. Holbrook.

INTRODUCTION.

In its investigations relating to the formation of carbon monoxide, the methods for its detection, the physiological effects upon miners and others, and the protective measures that are possible, the Bureau of Mines has studied the hazards due to the liberation of carbon monoxide from house heaters or stoves burning natural gas. Every year people are killed by breathing carbon monoxide given off by some type of heater used in homes. Although this paper covers only heaters burning natural gas, yet persons who use artificial gas may find the paper valuable. Tests of six common types of heaters and the method of testing are described, the results are discussed, and suggestions for minimizing the quantity of carbon monoxide emitted under certain conditions are presented.

The heaters were tested just as supplied by the manufacturer, without any adjustment. The tests were made in a closed room without ventilation. The gas used was burned at different rates of flow or consumption, and each heater was allowed to burn until the flames were extinguished by the lack of oxygen in the room. During each test the room atmosphere was sampled frequently and the samples were analyzed for carbon monoxide, carbon dioxide, oxygen, methane, and hydrogen. The tests represent conditions more dangerous than would ordinarily be found in a closed room in a house, because in the latter some air is always moving through the walls or around the doors and windows.

As a general conclusion regarding the tests herein reported, it may be said that in the majority of the tests not enough carbon monoxide was liberated to cause any alarm as to the use of natural-gas heaters or to necessitate any radical changes in their operation. Only under abnormal conditions, caused by faulty construction, excessive gas flow, or improper adjustments of the burner—as discussed later—did the carbon monoxide become dangerous. As a safety measure, however, a heater should not be allowed to burn in a closed room in which persons sleep at night, especially if the heater burns much gas and has no flue, unless one or more windows are open to supply plenty of fresh air. If this precaution is observed, there should be no loss of life by carbon monoxide poisoning during winter, when so many gas heaters are used in homes.

ACKNOWLEDGMENTS.

This investigation was made under the immediate direction of A. C. Fieldner, supervising chemist of the Pittsburgh experiment station. The authors are indebted to J. D. Davis and S. H. Katz for many valuable suggestions and criticisms; also to G. W. Smith and M. D. Hersey for assistance in deriving the equations for calculating the concentrations of carbon monoxide and diminution of oxygen; and further to W. P. Yant, of the gas laboratory, for assistance in making the tests and for general criticism.

COMBUSTION PRODUCTS FROM NATURAL GAS.

Combustion may be defined as any chemical process accompanied by the evolution of heat—commonly, the union of combustible substances with oxygen. The combustible constituents of natural gas are composed of the elements hydrogen and carbon and are known as saturated paraffin hydrocarbons. When natural gas is burning in a heater, the oxygen for combustion is supplied by the surrounding air. Normal air consists of 20.93 per cent oxygen, 79.04 per cent nitrogen,[1] and 0.03 per cent carbon dioxide.

When combustion is complete, the hydrogen in the hydrocarbons burns to water, and the carbon to carbon dioxide; but when not enough oxygen is supplied to the burning gases, or when under conditions like those in some of the tests described later the carbon is only partly oxidized by the oxygen, then carbon monoxide forms and escapes, with free hydrogen and unburned hydrocarbons of the natural gas itself. Furthermore, so-called "gas fumes" or "aldehyde odors" are liberated in small quantities, sometimes even when the combustion is practically complete. The significance of these gas-fume odors is discussed later.

All types of heaters must form carbon dioxide and water vapor; the volume liberated depends not on the type of heater but on the quantity of gas burned per hour. Each cubic foot of natural gas burned produces about 1 cubic foot of carbon dioxide and 2 cubic feet of water vapor, the amounts depending on the composition of the gas. The carbon dioxide causes no harmful physiological effects unless it is present in proportions greater than about 3 per cent; the water vapor causes no harm except by increasing the humidity of the atmosphere in the room. When this atmosphere becomes saturated with water vapor, moisture begins to condense on the windows and walls. The carbon monoxide resulting from incomplete combustion is the product that is dangerous to health, and if present in sufficient quantities it will cause death.

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[1] Including some of the rare inert gases, such as neon, krypton, and argon.

CARBON MONOXIDE.

PROPERTIES.

Carbon monoxide is produced when any carbonaceous substance burns without a sufficient supply of oxygen. In mines it is present in the afterdamp from explosions of fire damp (a mixture of air and 5½ to 14½ per cent methane) or of coal dust and from mine fires and in the gases from shots of explosives. Generally speaking, carbon monoxide does not support combustion, but 15 per cent of it in normal air makes an explosive mixture. Its ignition temperature is 644° to 658° C. (1,191° to 1,216° F.).

Slow burning with little heat creates more carbon monoxide than quick burning with great heat. Likewise more carbon monoxide is generated by fires in dead-end drifts, stopes, or raises, or in rooms of mines than there is in a place where the air is moving. Above ground this gas exists in artificial gases made from coal or oil, or in those from any combustion process where not enough oxygen is present to permit the carbon to burn completely to carbon dioxide.

Carbon monoxide is odorless, colorless, and tasteless, and can not be detected by any of the senses. It is so noxious that continued exposure to two-tenths of 1 per cent (0.2 per cent) of it will cause unconsciousness and death; and its effect is so insidious that a man breathing it may have little or no warning before he collapses. This gas combines with the hemoglobin in the red corpuscles of the blood, and temporarily renders them unable to absorb the oxygen of the air that enters the lungs. Thus the blood is unable to carry its proper supply of oxygen from the lungs to the cells and tissues of the body. As the affinity of carbon monoxide for hemoglobin is about 300 times as great as that of oxygen for hemoglobin, a very small percentage of carbon monoxide in air is highly dangerous.

TOXICITY.

Henderson[2] and others have found that when a person is at rest, an exposure of one hour to 0.03 per cent of carbon monoxide in normal air causes no ill effects; 0.06 per cent causes a perceptible effect; 0.09 per cent induces headache and nausea; and 0.15 per cent or more becomes dangerous to life. Tests made by Sayers and others[3] upon persons who were not exercising showed that exposure to 0.02 per cent of carbon monoxide for six hours produced very mild subjective symptoms of carbon monoxide poisoning; that is, yawning, slight tightness across the forehead, and sleepiness. One of the three subjects under observation reported a slight headache.

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[2] Henderson, Yandell, Haggard, H. W., Teague, M. C., Prince, A. L., and Wunderlich, R. M., Physiological effects of automobile exhaust gas, and standards of ventilation for brief exposures: Jour. Ind. Hygiene, vol. 3, 1920, p. 145.

[3] Sayers, R. R., Meriwether, F. V., and Yant, W. P., Effects of exposure to low concentrations of CO: Public Health Reports No. 19, vol. 37, 1922, pp. 1127-1142.

In view of these facts, the proportion of carbon monoxide in the rooms of a house whose occupants are continuously exposed to the gas should never be greater than one one-hundredth of 1 per cent (0.01 per cent). In this report this value is taken as the safe limit of concentration.

SYMPTOMS OF CARBON MONOXIDE POISONING.

Sayers and O'Brien,[4] discussing carbon monoxide poisoning, say that chronic poisoning produces a tired feeling, headache, nausea, palpitation of the heart, sleeplessness, and sometimes mental dullness; whereas a victim of acute carbon monoxide poisoning usually experiences the following symptoms: Yawning, sleepiness, tiredness, a feeling that the skin is tightly stretched across the forehead, and a frontal headache, at first dull and intermittent, and later more severe and continuous. Later, this headache is replaced or masked by a typical one at the base and back of the skull, which causes the sufferer to hold his head as far back as possible in an effort to obtain relief. Dizziness, nausea (feeling of sickness), and lassitude also occur. The pulse is at first normal, but later becomes full and rapid; the skin is flushed; the respiration becomes more rapid with exposure to the gas, and later irregular. If the exposure is sufficiently long, or the concentration sufficiently great, confusion and unconsciousness develop. The nausea may be sufficient to produce vomiting. All the symptoms are accentuated by exercise, eating, and stimulants. When a man is overcome by large concentrations of the gas, the symptoms follow each other rapidly, and he may quickly fall unconscious.

COMBUSTION OF NATURAL GAS.

COMPOSITION.

The natural gas from the gas fields of the United States contains only saturated paraffin hydrocarbons, variable amounts of carbon dioxide and nitrogen, and in certain localities small quantities of sulphur gases; it does not contain any hydrogen, carbon monoxide, or unsaturated hydrocarbons. In a few gas fields helium and other rare gases are associated with natural gas containing a large percentage of nitrogen.

The gaseous saturated paraffin hydrocarbons in natural gas are mainly methane and ethane, with small amounts of propane and butane; but the gas also carries vapors of liquid hydrocarbons, such as pentane and hexane. In some gas fields the natural gas contains only methane as the combustible gas, but in others it may contain all of the constituents named above.

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[4] Sayers, R. R., and O'Brien, H. R., Treatment of carbon monoxide poisoning: Reports of Investigations, Serial 2304, Bureau of Mines, December, 1921, 4 pp.

The usual gas analysis, by combustion methods, gives only the two predominating hydrocarbons, methane and ethane, or ethane and propane, depending on the proportions of the higher saturated hydrocarbons present. The average composition, calculated by the combustion method, of the natural gas used for the tests herein reported was as follows:

Analysis of natural gas.

	Per cent.
Carbon dioxide (CO_2)	0.0
Oxygen (O_2)	0.0
Methane (CH_4)	88.1
Ethane (C_2H_2)	10.3
Nitrogen (N_2)	1.6

AIR REQUIRED FOR COMBUSTION.

The amount of air necessary for the complete combustion of 1 cubic foot of natural gas of this composition is 10.14 cubic feet. If a gas heater is burning gas at a rate of 20 cubic feet per hour, then $10.14 \times 20 = 202.28$ cubic feet of air per hour, or 3.38 cubic feet per minute, will be required for complete combustion. Not only must this amount of air be supplied to the flame, but to insure complete combustion the above amount of air must be so intimately mixed with the gas that each molecule of gas will come in contact with enough oxygen to burn it to carbon dioxide and water vapor.

METHODS OF INTRODUCING AIR.

The most desirable way to accomplish the intimate mixing of air and gas is to introduce as large a volume of air as possible (up to nearly the lower explosive limit, or 5½ per cent of gas) into the gas before it reaches the burner ports. This is known as the "primary air supply." Combustion is completed by a smaller amount of "secondary air" drawn into the flame during the combustion process. Every heater should have suitable provision for the admission of this secondary air.

In the yellow-flame heater, where no primary air is added, all of the air for combustion reaches the flame as best as it can; consequently for a given consumption of gas, the flame spreads out and becomes much longer than it would if a primary air supply were admitted with the gas. If the burners are properly constructed, so that the proper amount of oxygen reaches the gas, combustion will be complete, as shown in Table 1 by tests 1, 2, 3, and 4. However, if the yellow flame impinges on metal or other surfaces, then, since combustion can take place only on the outer surface of the flame, part of the flame becomes smothered with its own products of combustion. Because of the insufficient supply of oxygen and the cooling of the flame, products of incomplete combustion—such as carbon monoxide, hydrogen, "aldehyde vapors" ("gas fumes"), and unconsumed methane and ethane—enter the room from the heater, as shown in Table 1 by test 5.

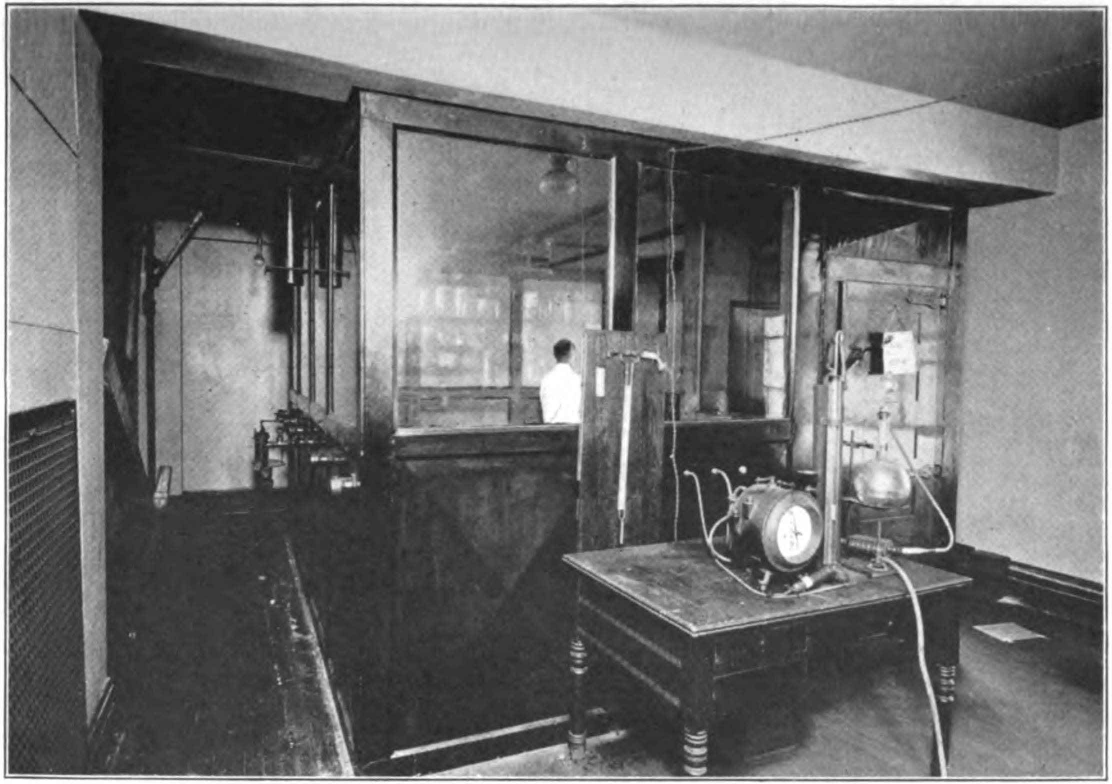
The preferable method of insuring rapid and, therefore, intensely hot combustion is to introduce primary air with the gas. In some types of heaters the combustion is further accelerated by surrounding the burning gas with incandescent materials, which by catalysis promote a more rapid union between the gas and air. However, dangers may attend this method, as is shown in Table 5 by test 1. If the gas flow exceeds a certain rate (15 cubic feet per hour in these tests), carbon monoxide is produced in appreciable quantities.

METHOD OF MAKING TESTS.

The tests were made in a closed room (Pl. I) of 1,000 cubic feet capacity. This room, which is for permanent use in the study of gases, is constructed of sheet iron and glass. The metal parts are soldered together and the glass windows are luted in with red lead and oil. Entrance is through two rubber-gasketed doors and a small anteroom which form an air lock, as shown in Plate I. Pipes from the tops of both the room and the anteroom lead to an exhaust fan, the inlet of which is closed by lowering seals containing mercury. These seals are operated from the outside by chains. Within the room a small fan keeps the atmosphere thoroughly circulated at all times, but does not cause draft effects.

Each heater tested was put in the room, and connected to the gas supply outside by a metal pipe. A wet meter connected to the pipe line determined the consumption of gas. With the exhaust outlets and both doors open, the heater was lighted and the gas regulated to give a certain flow or the desired height of flame. After the desired flow was obtained and the heater was burning steadily, the exhaust outlets and doors were closed, a time clock was started, the meter was read, and the temperature inside the room was recorded.

At one-half, one, or two hour periods, depending on the flow of gas, an observer recorded the meter and temperature readings; went into the room, took a sample of the atmosphere, and exposed a canary in the room for a definite period, usually three minutes. He also noted any odor and any irritating effects of the atmosphere. As the test proceeded and the oxygen content of the atmosphere in the room diminished, the flame in the heater lengthened, flickered, and eventually died out because of the deficiency of oxygen. A sample of the room atmosphere was taken and various data were recorded at the time the flame was extinguished. Usually the observer entered the room without protective apparatus; but when he suspected appreciable quantities of carbon monoxide he wore a carbon monoxide gas-mask.



INTERIOR OF ROOM IN WHICH HEATERS WERE TESTED

Samples of the room atmosphere were taken by the vacuum-tube method[5] and analyzed with the Bureau of Mines Haldane apparatus[6] for carbon dioxide, oxygen, carbon monoxide, methane, and hydrogen. Nitrogen was determined by difference. By this method the accuracy is about 0.02 per cent for each constituent. Samples showing very low percentages of carbon monoxide were tested qualitatively by the palladium chloride method.[7]

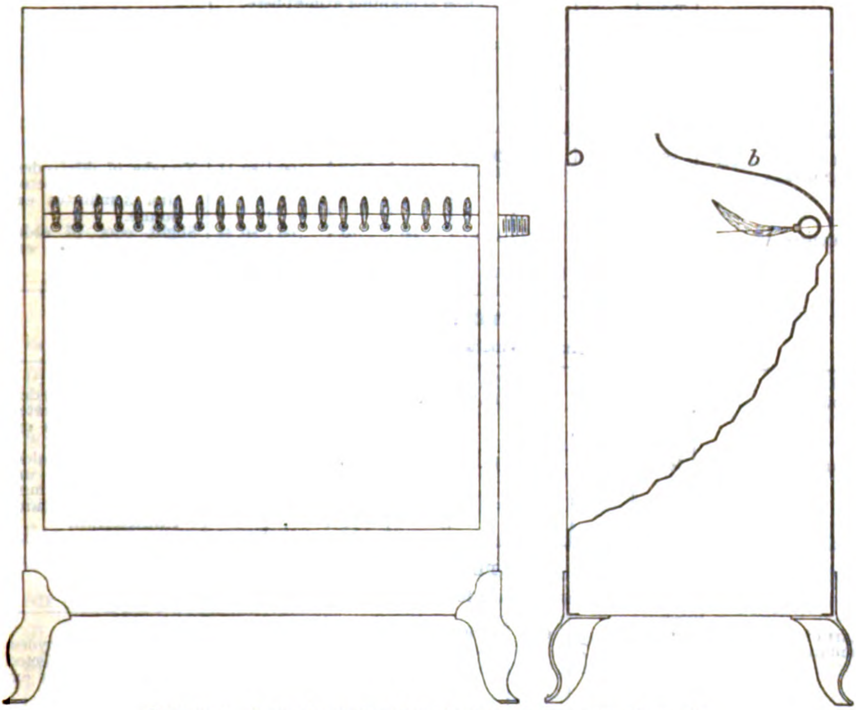


FIGURE 1.—Lava-tip, yellow-flame heater. No primary air supply.

TYPES OF HEATERS TESTED.

TYPE 1.—LAVA-TIP, YELLOW-FLAME HEATER.

Type 1 (Fig. 1) is in common use for natural gas. No primary air is admitted to the gas before it reaches the burner, which consists of a pipe with holes drilled along one side at about 2-inch intervals. Into these holes are screwed lava tips, from which the gas issues. The gas burns with a characteristic yellow flame, rather long and wavy. The gas is emitted at an angle and downward from the horizontal. This

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[5] Burrell, G. A., and Seibert, F. M., The sampling and examination of mine gases and natural gas: Bull. 42, Bureau of Mines, 1913, 116 pp.

[6] Jones, G. W., The Bureau of Mines Haldane apparatus: Its application and instructions for its use. Available for distribution in manuscript form.

[7] A dilute solution of palladium gives a positive test for carbon monoxide when the percentage present is 0.02 per cent or over, when 50 c. c. of the sample is taken, and the gas is allowed to remain in contact with the solution for two hours. A positive test is shown by the precipitation of fine specks of black, oily, metallic palladium on the surface of the solution.

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heater is fitted with the simplest type of burner tested; it has no primary air supply and only a plain cock for regulation of the gas. Results are shown in Table 1.

TABLE 1.—*Results of tests of a lava-tip, yellow-flame heater having 21 lava tips, each with an opening one-tenth inch in diameter.* (*See Fig. 1.*)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
TEST NO. 1. (Flame adjusted to extend 4 inches from tips and burn without touching reflector *b*.)									
Start of test	86.0	......	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	109.5	20.0	1.52	18.37	.00	.00	.00	80.11	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
46 minutes	106.0	20.1	1.95	17.67	.00	.04	.00	80.34	Slight odor of aldehydes. Flame extinguished.
TEST NO. 2. (Flame adjusted to extend 3 inches from tips; otherwise as in test No. 1.)									
Start of test	86.0	......	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	107.5	16.0	1.20	18.97	.00	.00	.00	79.83	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	104.0	15.3	2.02	17.67	.00	.07	.00	80.24	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure. Flame extinguished.
TEST NO. 3. (Flame adjusted to extend about 2 inches from tips; otherwise as in test No. 1.)									
Start of test	78.0	......	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	96.0	9.7	.83	19.54	.00	.00	.00	79.63	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	99.5	9.9	1.38	18.62	.00	.00	.00	80.00	Do.
1 hour 30 minutes	102.0	10.8	2.26	17.04	.00	.00	.00	80.70	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour 56 minutes	96.0	11.3	2.38	16.79	.00	.16	.00	80.67	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure. Flame extinguished.
TEST NO. 4. (Flame adjusted to extend about 1 inch from tips; otherwise as in test No. 1.)									
Start of test	82.5	......	0.03	20.93	0.00	0.00	0.00	79.04	
1 hour	89.0	5.0	.49	20.23	.00	.02	.00	79.26	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours	90.5	5.2	1.09	19.13	.00	.02	.00	79.76	Do.
3 hours	93.0	5.4	1.72	18.06	.00	.03	.00	80.19	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
3 hours 55 minutes	89.5	4.9	2.11	17.22	.00	.12	.00	80.55	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure. Flame extinguished.

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Table 1.—*Results of tests of a lava-tip, yellow-flame heater having 21 lava tips, each with an opening one-tenth inch in diameter*—Continued.

TEST NO. 5.

(Flame adjusted as in test No. 1, but with tips turned so that it impinged on metal reflector *b*.)

Time.	Temperature of chamber (inside °F.).	Gas rate, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test..........	88.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes...........	106.0	19.5	1.02	19.02	.12	.18	.00	79.66	Strong odor of aldehydes. Canary unable to stand up after 3 minutes exposure.
57 minutes...........	102.0	23.0	2.71	15.13	.63	1.68	.11	79.74	Very strong odor of aldehydes. Canary overcome in 20 seconds. Flame extinguished.

DISCUSSION OF RESULTS.

As the table shows, when the flame was allowed to burn without coming in contact with metal surfaces, carbon monoxide was not produced in detectable quantities at the four different gas flows tested, even when the percentage of oxygen was so low that the flame was extinguished. These results were confirmed by exposure tests of canaries. In none of these tests did the birds show symptoms of carbon monoxide poisoning when the gas was burned without the flame touching metal surfaces. In test 5 the direction of the flame was changed by turning the burner upward so that the flame impinged on the copper reflector *b* above the burner, as shown by the end view in Figure 1. Dangerous quantities of carbon monoxide were liberated under these conditions. With the heater consuming 19.5 cubic feet of gas an hour, in 30 minutes the air in the room contained 0.12 per cent carbon monoxide. A canary exposed for three minutes was unable to stand up but was not unconscious when removed. When the flame finally was extinguished, the atmosphere in the room contained 0.63 per cent of carbon monoxide, a concentration fatal to anyone breathing the atmosphere for only a few minutes. A canary was overcome in 20 seconds.

The test clearly shows the necessity of admitting a copious supply of oxygen to all sides of the flame of a heater of this type; it also shows that combustion takes place without coming in contact with metal surfaces, since no primary air is admitted into the gas, and all of the combustion must take place on the outer surface of the flame. Should the burning gas impinge upon a metal surface, not enough air reaches the gas, the flame is partly smothered, and a large amount of gas escapes without being burned. In addition, incomplete combustion produces free carbon, carbon monoxide, and hydrogen.

TYPE 2.—METAL-INCLOSED BLUE-FLAME HEATER WITH ADJUSTABLE PRIMARY-AIR INLET.

The type 2 heater (Fig. 2) is provided with an air shutter of the usual type to regulate the primary air supply before the gas-air mixture reaches the burner ports. The gas inlet is of the fixed type, having a diameter of 0.075 inch, and the rate of gas flow is changed by opening and closing the gas cock on the heater. The gas-air mixture issues from the burner through 75 ports, each 0.1 inch in diameter. The ports are arranged in three rows of 25 each in a zigzag manner. When the heater is normally operated the flames from the middle row are higher than the two outer rows, because the latter receive a larger supply of oxygen. Hence the middle row of flames has to take what oxygen is left after supporting the combustion of the two outer rows, and in consequence the flames of the middle row extend higher before combustion takes place. Viewed from one end the rows of flames resemble a cone, the highest point being at the middle; but at a low rate of gas consumption the flame is nearly level. Under the normal conditions of burning within the metal grid surrounding the flame, a localized higher temperature is produced, and good combustion results. The flames are blue except at the highest rate of flow tested, when they are tinged with yellow. The "spud" through which the gas was admitted to the burner was too small to admit 20 cubic feet of gas an hour with the pressure available (5.5 inches of water), therefore the heater was tested at 15, 10, and 5 cubic feet per hour.

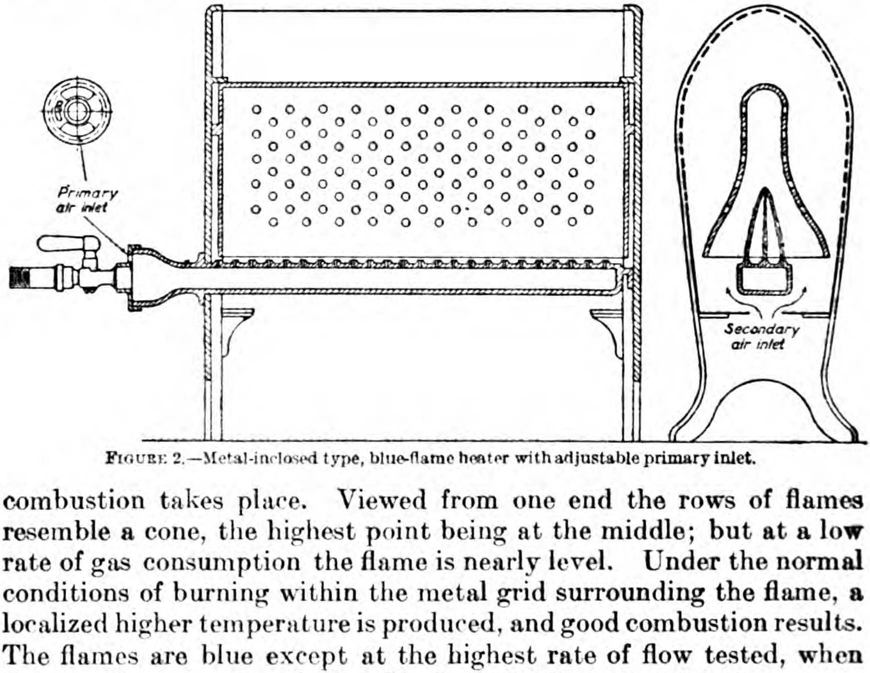

FIGURE 2.—Metal-inclosed type, blue-flame heater with adjustable primary inlet.

DISCUSSION OF RESULTS.

Tests 1, 2, and 3, as shown in Table 2, give the results obtained from this heater. No carbon monoxide was detected in the room atmosphere, at any rate of gas consumption, until the percentage of oxygen in the atmosphere fell to 15.66 per cent or lower. When the oxygen fell below this point, carbon monoxide was liberated in appreciable quantities, the maximum being 0.21 per cent.

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Table 2.—*Results of tests of a metal-inclosed blue-flame heater, with a shutter-type primary air inlet.* (*See Fig. 2.*)

TEST NO. 1.

(Gas-inlet valve wide open and heater tested at maximum capacity.)

Time.	Temperature of chamber (inside, °F.).	Gas rates, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test	84.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	102.0	15.5	1.12	19.03	.00	.02	.00	79.83	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	105.0	14.8	2.02	17.44	.00	.02	.00	80.52	Do.
1 hour 30 minutes	107.5	14.6	2.88	15.87	.00	.01	.00	81.24	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours 22 minutes	105.0	13.9	3.93	13.80	.21	.09	.00	81.97	Distinct odor of aldehydes. Canary slightly affected after 3 minutes exposure, although not overcome. Flame extinguished.

TEST NO. 2.

(Heater tested at two-thirds maximum capacity.)

Start of test	86.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	93.0	9.9	.75	19.69	.00	.00	.00	79.56	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	95.0	9.3	1.31	18.74	.00	.00	.00	79.95	Do.
1 hour 30 minutes	100.5	10.2	1.88	17.67	.00	.00	.00	80.45	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours	103.0	11.0	2.58	16.45	.00	.00	.00	80.97	Do.
2 hours 30 minutes	105.5	11.3	3.27	15.25	.00	.04	.00	81.44	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure.
3 hours	105.5	10.9	3.91	14.11	.00	.07	.00	81.91	Do.
3 hours 20 minutes	104.0	10.1	3.97	13.59	.09	.07	.00	82.28	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure. Flame extinguished.

TEST NO. 3.

(Heater tested at one-third maximum capacity.)

Start of test	80.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
1 hour	86.0	4.9	.70	19.79	.00	.00	.00	79.51	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours	88.0	4.3	1.20	18.87	.00	.00	.00	79.93	Do.
3 hours	90.5	5.3	1.85	17.75	.00	.00	.00	80.40	Do.
4 hours	93.0	5.6	2.52	16.61	.00	.00	.00	80.87	Do.
5 hours	92.5	5.1	2.97	15.66	.13	.00	.00	81.24	Distinct odor of aldehydes. Canary slightly distressed after 3 minutes exposure.
5 hours 47 minutes	92.5	5.1	3.28	15.07	.17	.07	.00	81.41	Distinct odor of aldehydes. Canary slightly distressed after 3 minutes exposure. Flame extinguished.

As the percentage of oxygen in the room became greatly diminished the flames spread out, because of the smaller proportion of oxygen in the primary air supply, until they burned through the perforations of the metal grid. These conditions caused a smothering and chilling effect on the flames, and carbon monoxide was produced.

TYPE 3.—ASBESTOS-BACK YELLOW-BLUE FLAME HEATER, WITH A FIXED PRIMARY AIR SUPPLY AND METAL AND MICA GUARD IN FRONT.

The type 3 heater is similar to the burner used in fireplaces. The burner (Fig. 3) consists of a cylindrical metal tube, 2 inches in diameter, having a series of small holes along the top from which the gas issues. The flame impinges on an upright asbestos reflector, back of the cylindrical tube. Gas is admitted to the burner from a nonadjustable spud, and a small amount of primary air is drawn in with the gas stream through a 1-inch circular hole cut into the tube. The amount of primary air drawn into the gas stream by this method is much smaller than by the more improved methods used in burners of types 2, 4, 5, and 6. The asbestos reflector is heated very hot by the flame and radiates into the room a part of the heat. Across the front of the heater is a flame guard consisting of a metal latticework with mica windows. The flame is somewhat luminous, but not as

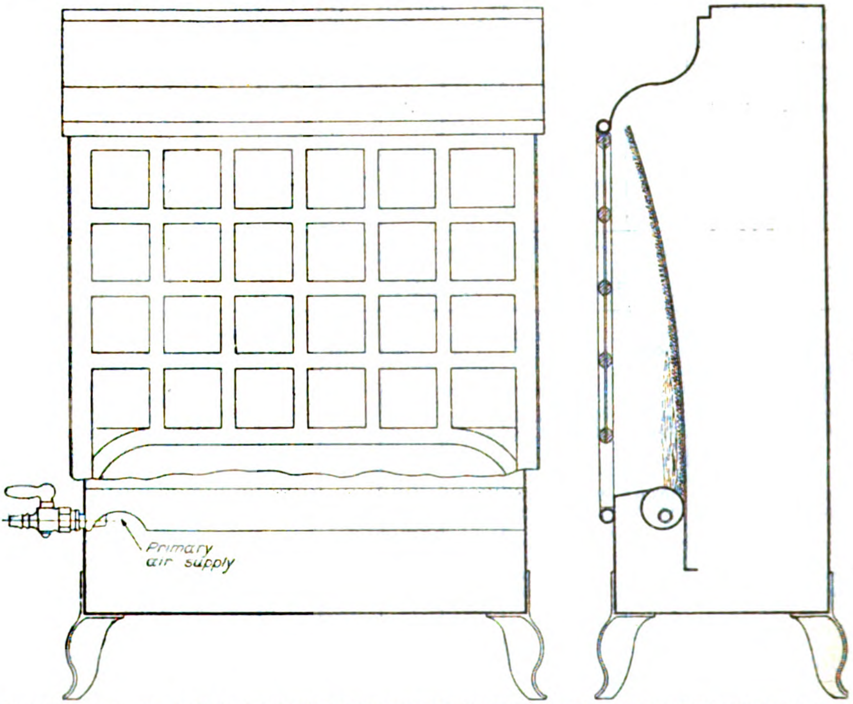

FIGURE 3.—Asbestos-back heater having fixed primary air supply, anda metal and mica guard in front of flame.

much as the flame of the type 1 heater. In the tests the length of the flame, which varied with the flow of gas, ranged from about 2½ inches to a length that entirely covered the asbestos back. Results are shown in Table 3.

DISCUSSION OF RESULTS.

When the consumption of gas was high (19 cubic feet an hour), carbon monoxide was liberated in exceedingly dangerous quantities and its concentration in the room at the end of the test was 1.72 per cent. It is also true that carbon monoxide was given off from the start, when the oxygen content of the room was nearly normal. Should the heater be operated as in this test in any room with no windows open, the atmosphere in the room would soon contain a very dangerous proportion of carbon monoxide.

TABLE 3.—*Results of tests of an asbestos-back, yellow-blue flame heater, having a fixed primary air mixer and a mica and metal guard in front of the flame.* (*See Fig. 3.*)

TEST NO. 1.

(Heater regulated so that flame extended from bottom to top of asbestos back.)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test	73.5	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	97.0	18.0	1.03	19.13	.29	.09	.16	79.30	Eyes irritated. Strong odor of aldehydes.
1 hour	98.5	19.2	1.59	17.29	.64	.19	.58	79.71	Atmosphere unbearable. Canary fell off perch in 10 seconds.
1 hour 30 minutes	99.5	19.8	2.13	16.10	1.00	.27	.63	79.87	Canary not taken in room.
2 hours	98.5	19.0	2.71	14.98	1.14	.75	.65	79.77	Do.
2 hours 32 minutes	93.0	19.5	3.07	14.50	1.72	.95	1.09	78.67	Flame extinguished.

TEST NO. 2.

(Heater regulated so that flame extended three-fourths from bottom to top of asbestos back.)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet, per hour.	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	Remarks.
Start of test	86.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	98.5	15.6	.99	19.30	.09	.03	.02	79.57	Distinct odor of aldehydes.
1 hour	101.0	14.6	1.65	17.91	.33	.11	.21	79.79	Strong odor of aldehydes. Irritation of the eyes.
1 hour 30 minutes	100.5	14.8	2.27	16.53	.58	.09	.28	80.25	Do.
2 hours	100.5	14.0	2.64	15.62	.64	.43	.36	80.31	Do.
2 hours 35 minutes	100.5	14.7	3.10	14.68	.71	.82	.46	80.23	Flame extinguished.

TEST NO. 3.

(Heater regulated so that flame extended about halfway from bottom to top of asbestos back.)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet, per hour.	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	Remarks.
Start of test	79.0	....	0.03	79.03	0.00	0.00	0.00	79.04	Canary put in chamber at beginning of test.
1 hour	93.0	9.5	1.24	18.89	.00	.00	.00	79.87	Odor of aldehydes and eye irritation. Canary somewhat distressed.
2 hours	97.0	9.8	2.38	16.83	.04	.05	.00	80.70	Very strong odor of aldehydes. Canary in great distress.
3 hours	97.0	10.2	3.24	15.46	.18	.19	.00	80.93	Canary dropped off perch after 2 hours 50 minutes. Could not be revived.
3 hours 26 minutes	97.0	9.0	3.51	14.64	.20	.32	.00	81.33	Flame extinguished.

TABLE 3.—*Results of tests of an asbestos-back, yellow-blue flame heater, having a fixed primary air mixer and a mica and metal guard in front of the flame*—Continued.

TEST NO. 4.

(Heater regulated so that flame was about 2½ inches long.)

Time.	Temperature of chamber (inside °F.).	Gas rate, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test..........	79.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
2 hours..............	82.5	4.7	1.29	18.73	.02	.00	.00	79.96	Slight odor of aldehydes.
4 hours..............	87.0	5.0	2.40	17.11	.03	.01	.00	80.45	Distinct odor of aldehydes. Slight irritation of nose.
6 hours..............	87.0	5.0	3.34	15.21	.07	.11	.00	81.27	Strong odor of aldehydes.
7 hours 9 minutes....	89.0	5.5	3.62	14.45	.13	.26	.00	81.54	Flame extinguished.

TEST NO. 5.

(Heater regulated to same rate as test No. 1 but guard on front of heater removed.)

Time.	Temperature of chamber (inside °F.).	Gas rate, cubic feet, per hour.	CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	Remarks.
Start of test..........	76.5	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes...........	108.0	19.0	1.28	18.79	.04	.00	.00	79.89	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure in chamber.
1 hour...............	113.0	18.0	2.53	16.55	.05	.02	.00	80.85	Canary not taken into room. Distinct odor of aldehydes.
1 hour 22 minutes....	106.0	20.5	3.00	15.66	.05	.17	.00	81.12	Canary unaffected after 3 minutes exposure Flame extinguished.

As the flow of gas was decreased, the emission of carbon monoxide lessened, as shown by tests 2, 3, and 4. Test 5 was made under the same conditions as test 1, in which much carbon monoxide was produced, except that the guard was removed to allow more air to reach the flame. In test 5 very little carbon monoxide was produced, there being only 0.05 per cent in the room when the flame was extinguished. In tests 1, 2, and 3, the guard kept secondary air enough to insure complete combustion from getting to the flame; and therefore carbon monoxide was liberated. When enough air was permitted to reach the flame, very little carbon monoxide formed, showing that its liberation was not primarily due to a fault of the burner design, or to the asbestos back, but rather to the guard smothering the flame. As a heater burning gas at the rate of 20 cubic feet an hour must be supplied with about 3.4 cubic feet of air a minute to insure complete combustion, it obviously is essential that every natural-gas heater be so made that a copious supply of air reaches the burning gas. Guards, if put around a heater, should be far enough from the burner, and they should have plenty of openings to permit air to be easily drawn into the burning gas. A simple provision would be to have nothing but a fairly coarse wire screen in front of the flame.

Table 4.—*Results of tests of a cylindrical, blue-flame bathroom heater protected outside by a perforated shield.* (*See Fig. 4.*)

TEST NO. 1.

(Heater operated with gas-admission valve wide open.)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test	77.0	......	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	102.0	14.7	1.13	19.07	.00	.00	.00	79.80	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	108.5	15.7	2.07	17.37	.00	.00	.00	80.56	Do.
1 hour 32 minutes	102.0	15.0	2.76	16.00	.09	.13	.00	81.02	Strong odor of aldehydes. Canary unaffected after 3 minutes exposure. Flame extinguished.

TEST No. 2.

(Heater operated with gas-admission valve two-thirds open.)

Start of test	82.5	......	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	95.0	10.1	.76	19.68	.00	.03	.00	79.53	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	97.5	9.6	1.36	18.60	.00	.04	.00	80.00	Do.
1 hour 30 minutes	99.5	9.3	1.96	17.54	.00	.04	.00	80.46	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours	100.5	10.0	2.49	16.61	.08	.06	.00	80.76	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours 19 minutes	95.0	9.8	2.62	16.20	.16	.53	.00	80.49	Distinct odor of aldehydes. Canary in distress after 3 minutes exposure. Flame extinguished.

TEST No. 3.

(Heater operated with gas-admission valve one-third open.)

Start of test	80.5	......	0.03	20.93	0.00	0.00	0.00	79.04	
1 hour	88.0	5.4	.78	19.64	.00	.00	.00	79.58	No odor of aldehydes, Canary unaffected after 3 minutes exposure.
2 hours	89.5	5.1	1.36	18.64	.00	.00	.00	80.00	Do.
3 hours	91.5	5.3	2.01	17.52	.00	.00	.00	80.47	Do.
4 hours	91.5	5.7	2.50	16.59	.04	.04	.00	80.83	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure.
5 hours	89.0	4.9	2.69	16.16	.08	.31	.00	80.76	Strong odor of aldehydes. Canary unaffected after 3 minutes exposure. Heater turned out.

TYPE 4.—CYLINDRICAL, BLUE-FLAME BATHROOM HEATER, PROTECTED ON OUTSIDE BY PERFORATED METAL SHIELD.

The type 4 heater (Fig. 4) is well known. Its burner has an adjustable primary air supply, and the flame is entirely inclosed by a perforated sheet-metal cone. The gas flows into the mixing tube from a nonadjustable orifice. The burner ports, 50 in all, have a diameter of 0.1 inch. Secondary air is supplied through holes in an asbestos mat below the burner.

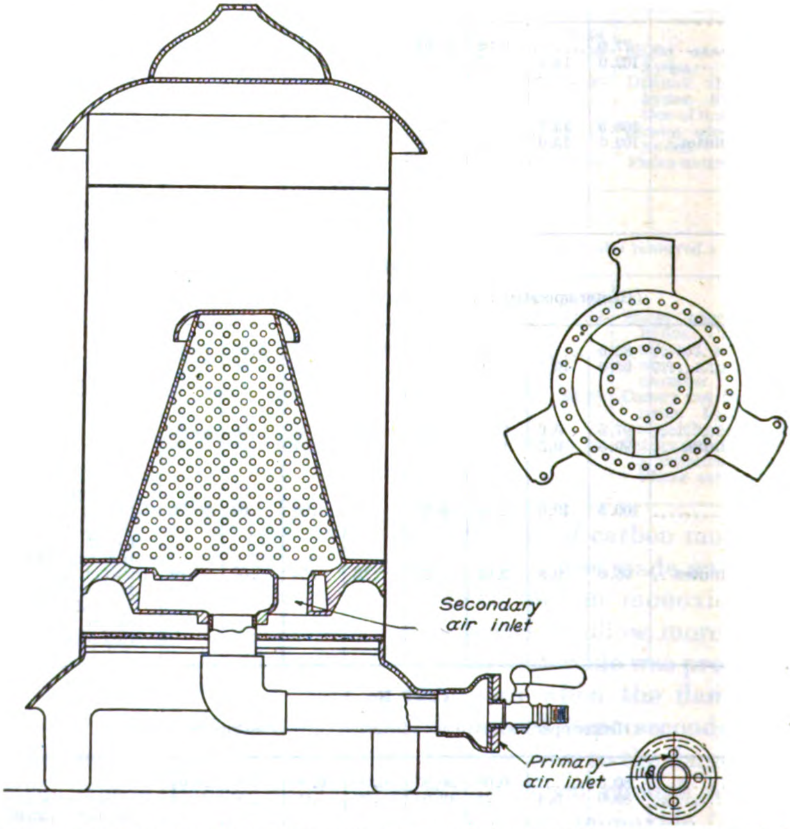

FIGURE 4.—Cylindrical, blue-flame bathroom heater, protected on outside by perforated metal shield. Gases burned within a metal cone over ports. Supplied with adjustable primary air inlet.

DISCUSSION OF RESULTS.

Tests 1, 2, and 3 in Table 4 give the results obtained with different gas rates. The shutter of the primary air valve was left wide open in all tests. The flow of gas ranged from one-third to maximum capacity. The gas inlet prevented rates higher than that given by test 1. In the tests carbon monoxide was not formed in detectable quantities until the percentage of oxygen in the room was reduced almost to the point at which the flame went out; then appreciable quantities were produced as a result of the lengthening of the flame. Such a condition, however, would seldom if ever occur in the normal usage of the heater.

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TYPE 5.—RADIANT NONLUMINOUS FLAME HEATER WITH ADJUSTABLE ORIFICE FOR GAS AND FIXED PRIMARY AIR SUPPLY.

In the type 5 heater (Fig. 5) the gas is admitted through a variable orifice, and in passing to the burners it draws in the primary air from a nonadjustable opening. The gas issues from 10 burner openings and is burned within the so-called radiants, which become very hot and radiate a large part of the heat. This heater was tested as supplied by the manufacturer. In the tests the valve on the pipe line was opened as far as possible, and the flow of gas was regulated by screwing down the adjustable orifice at the heater. Results are shown in Table 5.

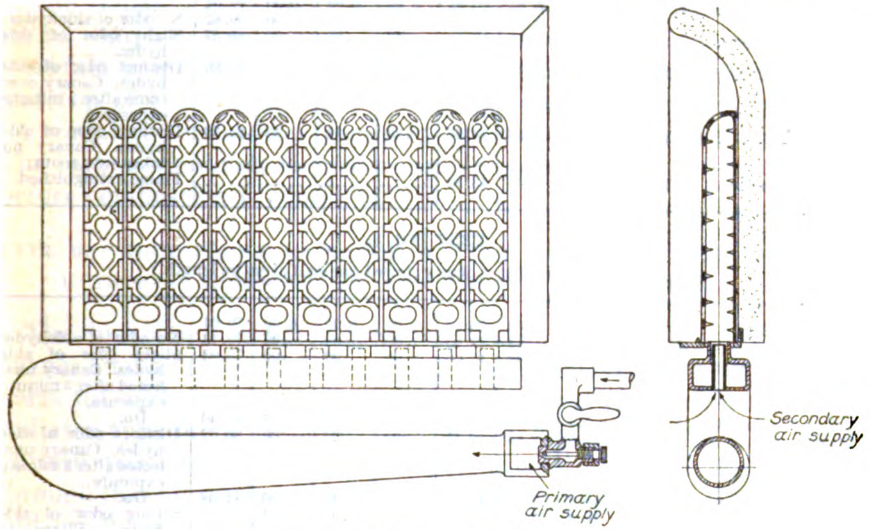

FIGURE 5.—Radiant-type nonluminous heater.

TABLE 5.—*Results of tests of a radiant-type nonluminous heater having an adjustable orifice for gas and a fixed primary air supply.*

TEST NO. 1.

(Heater regulated so that radiants glowed throughout entire length.)

Time.	Temperature of chamber (inside, °F.).	Gas rates, cubic feet, per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test	81.5	......	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	104.0	18.5	1.27	18.76	.02	.02	.00	79.93	No odor of aldehydes. Canary unaffected after 3 minutes exposure in room.
1 hour	109.5	18.5	2.38	16.66	.12	.11	.07	80.66	Slight odor of aldehydes. Canary fell off perch after 3 minutes exposure.
1 hour 30 minutes	116.5	19.6	3.28	15.04	.20	.20	.05	81.23	Strong odor of aldehydes and irritated the eyes. Canary unconscious after 3 minutes exposure.
1 hour 51 minutes	115.0	18.6	3.92	13.83	.32	.35	.05	81.53	Flame extinguished.

TABLE 5.—*Results of tests of a radiant-type nonluminous heater having an adjustable orifice for gas and a fixed primary air supply*—Continued.

TEST NO. 2.

(Heater regulated so that radiants glowed three-fourths of entire length.)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet per hour.	Composition of chamber atmosphere, per cent.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test	82.5	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	100.5	14.6	1.18	18.98	.00	.02	.00	79.82	No odor of aldehydes.
1 hour 30 minutes	104.0	14.2	2.11	17.38	.10	.02	.02	80.37	Slight odor of aldehydes.
1 hour 30 minutes	107.0	15.8	2.83	15.88	.23	.09	.11	80.86	Distinct odor of aldehydes. Canary overcome after 3 minutes exposure.
2 hours	109.5	16.0	3.58	14.56	.33	.11	.13	81.29	Distinct odor of aldehydes. Canary not taken into room.
2 hours 24 minutes	105.0	14.2	3.93	13.89	....	....	....	....	Flame extinguished.

TEST NO. 3.

(Heater regulated so that radiants glowed one-half of entire length.)

Start of test	80.5	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	92.5	9.4	.71	19.86	.00	.00	.00	79.43	No odor of aldehydes.
1 hour	96.0	9.9	1.42	18.65	.00	.00	.00	79.93	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour 30 minutes	98.5	9.8	2.04	17.53	.03	.00	.00	80.40	Do.
2 hours	100.5	10.3	2.63	16.45	.05	.05	.00	80.82	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours 30 minutes	104.0	10.3	3.05	15.63	.05	.19	.00	81.08	Do.
3 hours 26 minutes	100.5	10.3	3.81	14.27	.20	.34	.01	81.37	Strong odor of aldehydes. Flame extinguished.

TEST NO. 4.

(Heater regulated so that radiants glowed one-fourth of entire length.)

Start of test	79.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
2 hours	89.5	5.0	1.38	18.78	.00	.01	.00	79.83	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
4 hours	91.5	5.2	2.59	16.50	.00	.01	.00	80.90	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
4 hours 35 minutes	89.0	4.8	2.70	16.40	.00	.14	.00	80.76	Distinct odor of aldehydes. Flame extinguished.

DISCUSSION OF RESULTS.

The tests were made to cover the different rates at which the gas might be burned, and in Table 5 these rates are grouped in the table by the extent of glowing of the radiants. As the table shows, carbon monoxide was not liberated in detectable quantities until the percentage of oxygen in the room was less than 19 per cent; but considerable quantities were emitted as the percentage of oxygen became lower. The quantity was especially large at the higher rates of gas consumption and at the point where the flame was extinguished, as in tests 1 and 2, where it was over 0.30 per cent. With a consumption of 5 cubic feet of gas an hour no carbon monoxide was liberated, even at the time when the flame was extinguished.

This formation of carbon monoxide at high rates of gas consumption was due to the amount of primary air admitted with the gas being insufficient to burn the gas completely and to the gas burning in the radiants being prevented from drawing in enough secondary air to complete combustion. When the consumption of gas reaches a certain point, the combustion products pass out through the sides and top of the radiant, and thus keep the secondary air necessary for complete combustion from getting into the interior of the radiant. The carbon monoxide formed escapes from the outside of the radiant before combustion is complete.

TYPE 6.—BLUE-FLAME RADIATOR HEATER WHOSE COMBUSTION PRODUCTS PASS THROUGH AN ABSORBENT BEFORE LIBERATION.

The blue-flame radiator heater is shown in Figure 6. It has a burner similar to that of the type 2 heater. The gas issues from 39 ports 0.1 inch in diameter, and the whole burner is mounted in a radiator-type metal frame so constructed that the products of combustion pass up through the center, then divide and come down through the end sections, pass up again through the lower central part, and finally out through a canister on the back. The canister contains a chemical for removing "noxious gases" in the combustion products. In outward appearance the radiator closely resembles a hot-water radiator. Results are given in Table 6.

DISCUSSION OF RESULTS.

In test 1 the consumption of gas was the highest possible with the gas pressure available—5.5 inches of water. Test 2 was at half capacity; test 3 was the same as test 1, but with the canister removed; and test 4 was made after the heater had been used two months and about 3,500 cubic feet of gas had been consumed. Tests 1 and 2 were made with fresh chemical in the canister.

The tests indicate that carbon monoxide is not liberated until the oxygen content of the air supplied the heater falls below 19 per cent, but when the oxygen content of the air is so low that the flame is almost extinguished appreciable quantities of carbon monoxide are produced. Tests 3, with the canister removed, otherwise same as test 1, indicates that the chemical has no appreciable effect on the carbon dioxide or carbon monoxide content of the liberated products of

TABLE 6.—*Results of tests of a blue-flame radiator heater. Combustion products circulate through the radiator and a canister containing chemical before escaping into the room.*

TEST 1.

(Gas-admission valve wide open.)

Time.	Temperature of chamber (inside, °F.).	Gas rate, cubic feet per hour.	Composition of chamber atmosphere.						Remarks.
			CO_2.	O_2.	CO.	CH_4.	H_2.	N_2.	
Start of test	87.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	95.0	11.4	.85	19.68	.00	.00	.00	79.47	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	100.5	11.5	1.53	18.38	.03	.02	.00	80.04	Do.
1 hour 40 minutes	101.5	11.1	2.33	16.77	.12	.02	.00	80.76	Slight odor of aldehydes. Flame extinguished.

TEST 2.

(Gas-admission valve half open.)

Start of test	84.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
1 hour	91.5	5.1	.71	19.80	.00	.00	.00	79.49	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
2 hours	95.0	5.2	1.32	18.64	.00	.03	.00	80.01	Do.
3 hours	97.0	4.9	1.83	17.75	.00	.03	.00	80.39	Do.
3 hours 55 minutes	98.0	4.9	2.28	16.94	.00	.08	.00	80.70	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure.

TEST 3.

(Gas-admission valve wide open: canister containing chemical removed.)

Start of test	78.0	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	88.0	10.4	.76	19.66	.00	.00	.00	79.58	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	94.0	10.9	1.40	18.55	.04	.06	.00	79.95	Very strong odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour 12 minutes	94.0	10.4	1.47	18.40	.06	.08	.00	79.99	Do.

TEST 4.

(Gas-admission valve wide open; tested after heater had been used a month.)

Start of test	82.5	....	0.03	20.93	0.00	0.00	0.00	79.04	
30 minutes	92.5	10.0	.70	19.85	.00	.00	.00	79.45	No odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour	97.0	9.5	1.32	18.77	.00	.00	.00	79.91	Do.
1 hour 30 minutes	100.5	9.7	1.88	17.75	.04	.00	.00	80.33	Slight odor of aldehydes. Canary unaffected after 3 minutes exposure.
1 hour 51 minutes	101.5	9.6	2.18	17.11	.08	.05	.00	80.58	Distinct odor of aldehydes. Canary unaffected after 3 minutes exposure. Flame extinguished.

combustion, but lessens the aldehyde odors or gas fumes. Also the removal of the canister increased the draft with the result that the flame was extinguished when the percentage of oxygen in the room dropped to 18.40 per cent.

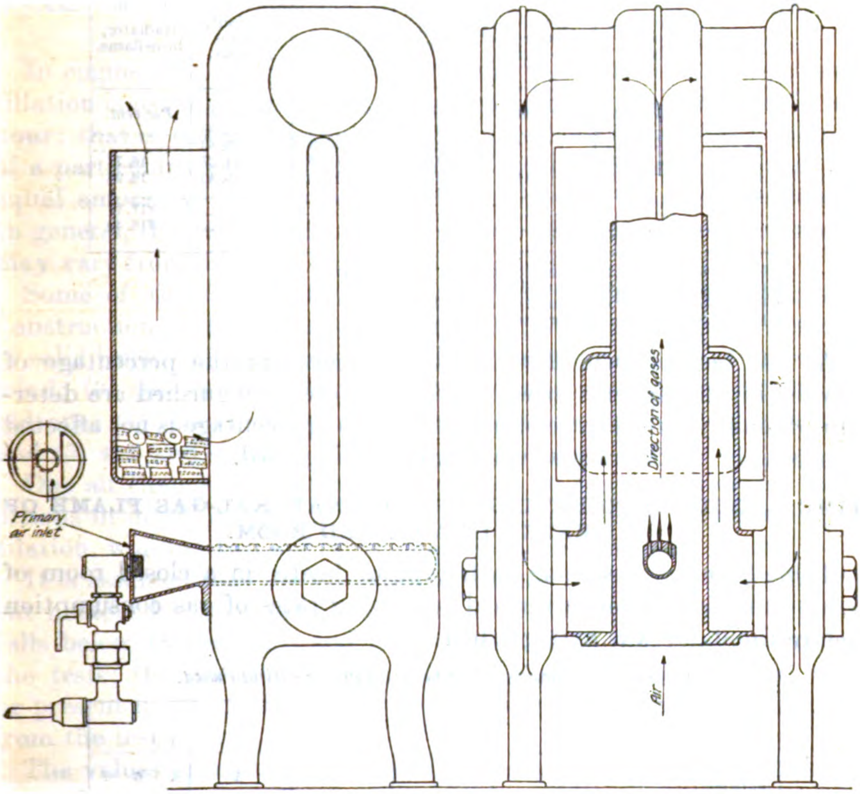

FIGURE 6.—Radiator-type heater with attachment for removing "noxious gases."

PERCENTAGE OF OXYGEN PRESENT AT THE MOMENT THE FLAMES OF NATURAL-GAS HEATERS ARE EXTINGUISHED.

In all of the tests that were started with normal air containing 20.93 per cent of oxygen and were continued until the flames went out, the flames became wavy and longer as the oxygen decreased until just before extinction their length, measured from the point at which the gas issued from the burner ports, was several inches. Under these conditions rather large quantities of natural gas escaped unburned into the atmosphere. The heaters were allowed to burn as long as flame could be seen, and when it finally disappeared the gas was turned off and a sample of the atmosphere was taken for analysis. The oxygen content at which the flames were extinguished is given in Table 7.

TABLE 7.—*Oxygen content of atmosphere when flames of different heaters were extinguished—per cent by volume.*

Gas flow per hour.	Type of heater.					
	1	2	3	4	5	6
	Lava tip, yellow-flame.	Metal-inclosed blue-flame.	Asbestos-back, blue-yellow flame.	Metal-inclosed blue-flame.	Radiant, nonluminous.	Radiator, blue-flame.
Cu. ft.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
20	17.67	....	14.50	....	13.83	....
15	17.67	13.80	14.68	16.00	13.89	....
10	16.79	13.59	14.64	16.20	14.27	16.77
5	17.22	15.07	14.45	16.16	16.40	16.94
20	[a]15.13	....	[b]15.66	....	....	....
10	....	....	....	....	....	[c]17.11
10	....	....	....	....	....	[d]18.40

[a] Heater tested with flame impinging on a metal surface.
[b] Heater tested with front guard removed.
[c] Heater tested after being used for 1 month.
[d] Heater tested with canister removed.

As has been shown, these wide differences in the percentage of oxygen in atmospheres in which flames were extinguished are determined mainly by the type of heater, and the percentage is not affected appreciably by the rate at which gas is being used.

TIME REQUIRED TO EXTINGUISH THE NATURAL-GAS FLAME OF A HEATER IN A CLOSED ROOM.

Table 8 shows how long each type of heater in a closed room of 1,000 cubic feet capacity burned at varying rates of gas consumption before the flame was extinguished:

TABLE 8.—*Time required before flame is extinguished.*

Approximate gas flow per hour.	Type of heater.											
	1		2		3		4		5		6	
	Lava tip, yellow-flame.		Metal-inclosed, blue-flame.		Asbestos-back, yellow-blue flame.		Metal-inclosed, blue-flame.		Radiant, nonluminous flame.		Radiator, blue-flame.	
Cu. ft.	*Hr.*	*min.*	*Hr.*	*min.*	*Hr.*	*min.*	*Hr.*	*min.*	*Hr.*	*min.*	*Hr.*	*min.*
20	—	46	—	—	2	32	—	—	1	51	—	—
20	—	[a]57	—	—	1	[b]22	—	—	—	—	—	—
15	1	00	2	22	2	35	1	32	2	24	—	—
10	1	56	3	20	3	26	2	19	3	26	1	40
5	3	55	5	47	7	9	5	00	4	35	3	55
10	—	—	—	—	—	—	—	—	—	—	[c]1	12

[a] Heater tested with flame impinging on copper reflector.
[b] Heater tested with guard removed.
[c] Heater tested with canister removed.

The period a heater will burn in a closed room before the flame goes out depends on the size of the room, the gas flow, and the type and adjustment of the heater. In the room of 1,000 cubic feet, made of metal and glass through which gases could not diffuse, the time ranged from 46 minutes to 7 hours 9 minutes, as shown in Table 8. It is obvious that any gas heater burning at any rate of gas consumption in a hermetically tight room will eventually reduce the oxygen to the point where the flame will go out. Even in tightly closed rooms of dwellings, however, there is generally some ventilation by air passing through the walls or around doors and windows.

MAXIMUM ACCUMULATION OF CARBON MONOXIDE IN A VENTILATED ROOM.

In engineering problems relating to the ventilation of houses, ventillation is usually stated in terms of the number of air changes in an hour; that is, one air change means that fresh air equal to the volume of a particular room has been admitted during one hour and that an equal amount of air has been displaced by the incoming fresh air. In general, the number of air changes that take place in a given room may vary from a half to three or more an hour.

Some of the factors determining air change are as follows: (1) Construction of the house—whether frame, brick veneer, tile, stucco, or solid brick; (2) exposure to wind and velocity and direction of the wind; (3) age—a new house being more impervious to gases than an old one; (4) number of windows and doors in the particular room; and (5) size and shape of the room.

One air change an hour has been taken to represent average conditions in most rooms. A half air change represents very poor ventilation, whereas two and three changes mean good ventilation.

It is assumed that the liberation of carbon monoxide by the different heaters tested is fairly constant until the percentage of oxygen falls below 18 per cent, and this assumption is fairly borne out by the tests; the maximum percentage of carbon monoxide that will be present in a room at a given rate of ventilation may be calculated from the test figures.

The values given in column 4 of Table 9 were obtained by taking from Tables 1 to 6 only those tests in which carbon monoxide was given off when the atmosphere in the test room contained 18 per cent or more of oxygen and by calculating for those tests the average cubic feet of carbon monoxide liberated in an hour.

CARBON MONOXIDE PERCENTAGES AT DIFFERENT AIR-CHANGE RATES.

The percentages of carbon monoxide (Table 9) at different air-change rates an hour were calculated by using this equation:

$$C=\frac{100\,K}{RV}\left(1-e^{-Rt}\right)$$

Where C = percentage of CO in a room after a given time,
R = air changes per hour,
t = time in hours,
V = volume of room in cubic feet,
K = cubic feet of carbon monoxide liberated by heater per hour.

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The above equation is derived as follows:

$$dM = Kdt - \frac{M}{V}\,dv \qquad (1)$$

Call $R = \frac{1}{V}\frac{dv}{dt} \therefore \frac{dv}{V} = Rdt$ and (1) becomes

$$dM = Kdt - MRdt$$

$$\therefore \int_0^M \frac{dM}{K - MR} = \int_0^t dt \qquad (2)$$

Integrating, $\log \frac{K - MR}{K} = -Rt$

$$\therefore \frac{K - MR}{K} = e^{-Rt}$$

Solving for M,

$$M = \frac{K}{R}\left(1 - e^{-Rt}\right) \qquad (3)$$

But by definition, $C = \frac{M}{V}$, or, in per cent (3) becomes

$$C = 100\,\frac{K}{RV}\left(1 - e^{-Rt}\right) \qquad (4)$$

TABLE 9.—*Percentage of carbon monoxide that would accumulate in a room of 1,000 cubic feet capacity, ventilated at varying air-change rates an hour, from different types of heaters burned continuously for one and for five hours.*

1	2	3	4	5	6	7	8	9	10	11	12
Type.	Test No.	Gas rate, cubic feet per hour.	CO liberated, cubic feet per hour.	CO in room at end of 1 hour, per cent.				CO in room at end of 5 hours, per cent.			
				Air changes per hour.				Air changes per hour.			
				0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0
[a] 1	5	19.5	2.4	0.19	0.15	0.10	0.08	[f] 0.44	[f] 0.24	[f] 0.12	[f] 0.08
[b] 3	1	18.6	5.8	.46	.37	.25	.18	[f] 1.06	[f] .58	[f] .29	[f] .19
[b] 3	2	15.1	3.3	.26	.21	.14	.10	[f] .61	[f] .33	[f] .16	[f] .11
[b] 3	3	9.7	.2	.02	.01	.01	.01	.04	.02	.01	.01
[b] 3	4	4.9	.1	.01	.01	.01	.01	.02	.01	.01	.01
[c] 3	5	18.5	.5	.04	.03	.02	.02	[f] .09	[f] .05	.02	.02
[d] 5	1	18.5	.4	.03	.03	.02	.01	[f] .07	.04	.02	.01
[e] 6	1	11.5	.3	.02	.02	.01	.01	[f] .06	.03	.01	.01
[e] 6	2	5.1	.1	.01	.01	.01	.01	.02	.01	.01	.01

[a] Lava-tip, yellow-flame type with flame turned to impinge against metal reflector.
[b] Asbestos-back, yellow-blue flame type with metal protector on front of heater.
[c] Asbestos-back type with metal protector removed.
[d] Radiant nonluminous-flame type.
[e] Blue-flame radiator type having canister to remove fumes.
[f] Dangerous condition.

DISCUSSION OF RESULTS.

All of the tests at one-half air change an hour—very poor ventilation—show that dangerous quantities of carbon monoxide would accumulate in a room of 1,000 cubic feet capacity in a period of five hours.

At one air change an hour—normal ventilation—all of the heaters except type 3, in tests 3 and 4, and type 6, in test 1, indicated that dangerous amounts of carbon monoxide would accumulate. At two and three air changes an hour—good ventilation—only the yellow-flame heater with flame impinging on the metal reflector, the asbestos-back heater with a metal guard across its front, when consuming gas at a rate greater than 10 cubic feet per hour, and the radiant type, when using 18.5 cubic feet per hour, indicated dangerous amounts of carbon monoxide.

The equation used to compute the amount of carbon monoxide that accumulates in a given time (Table 9) when used for different time intervals shows that the carbon monoxide in a room increases rapidly at first, and then approaches a constant value that is not exceeded. This equilibrium value is reached much more quickly at the higher air-change rates than at the lower, as is shown by the curves in Figure 7, plotted from one of the tests (type 3, test 1, Table 9), in which the highest amount of carbon monoxide, 5.8 cubic feet an hour, was emitted.

In Figure 7 the top curve shows that 12 hours would be required for the percentage of carbon monoxide to reach a maximum in a room where the air-change rate is 0.5 per hour; it also shows that the final maximum percentage is equal to twice the percentage reached in one hour with no ventilation. At one air change an hour the maximum percentage, reached in about five hours, is equal to the amount reached in one hour with no ventilation. At two air changes an hour the maximum percentage is reached in about three hours, and equals half the amount that would accumulate without ventilation in one hour. At three air changes an hour the maximum percentage is reached in about two hours, and equals one-third the amount of carbon monoxide that would be produced in one hour without ventilation. These conclusions hold true regardless of the size of the room, because in the equation from which these values were derived the volume of the room is a constant for any given set of tests.

ARE "GAS FUMES" AN INDICATION OF CARBON MONOXIDE?

When most stoves and heaters burning natural gas are first lighted, especially if the flame comes in contact with cold-metal surfaces, a characteristic "gas fume" odor is produced. If concentrated enough, these gas fumes irritate the eyes, causing them to water and become inflamed; they also attack the mucous membrane of the nose and throat, causing a stinging sensation and coughing. Although never definitely identified, these fumes consist mainly of mixtures of aldehyde vapors, produced by the interaction of water vapor, oxygen, and methane under conditions that retard combustion and prevent the methane and oxygen from burning completely to carbon dioxide

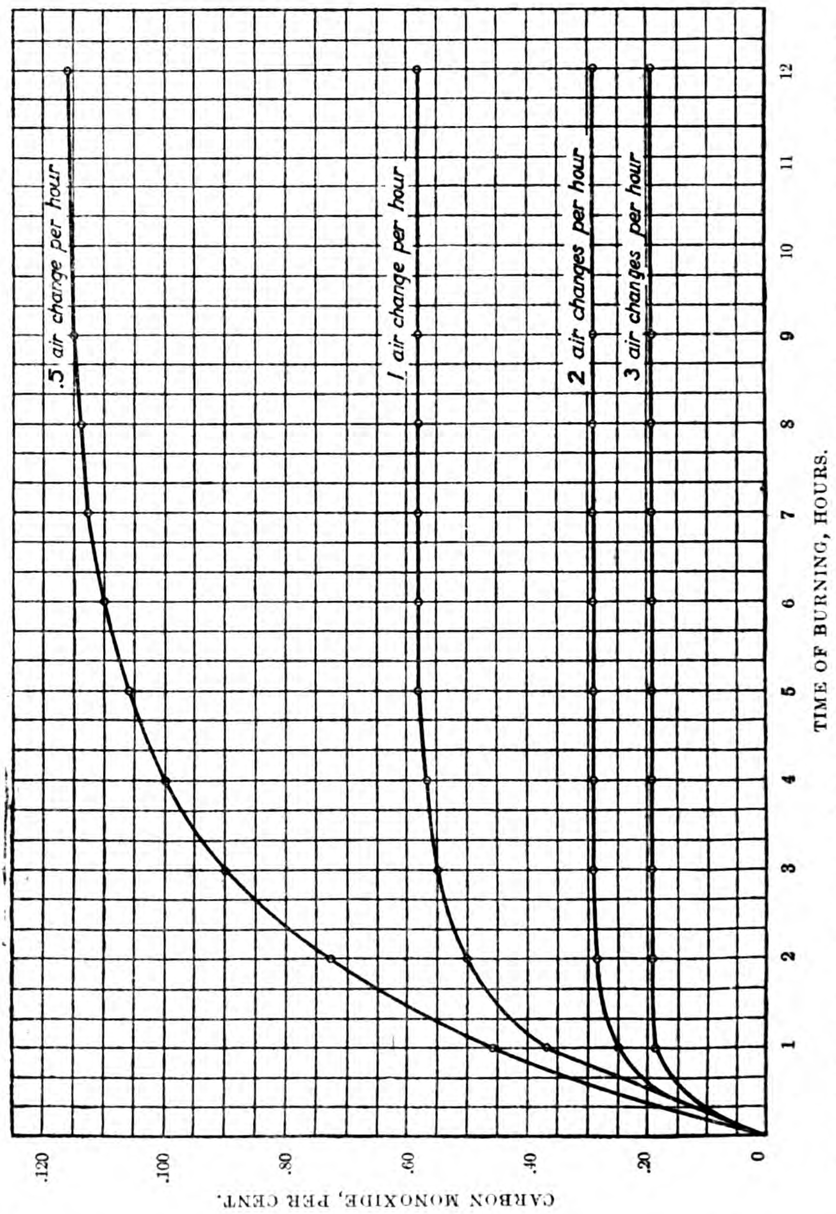

FIGURE 7.—Curves showing percentage of CO that would accumulate at varying air-change rates in a room having a capacity of 1,000 cubic feet.

and water vapor. When the metal surfaces become hot enough, the aldehyde vapors formed are decomposed, and usually (except in gas-burning hot-water heating systems) largely disappear after the first few minutes of combustion, unless the stove continues to burn under conditions that tend to cool and smother the flame. It is these vapors that are usually confused with carbon monoxide. A heater that gives off gas fumes is usually suspected of liberating carbon monoxide.

The tests made in this report afford data by which the relation of gas fumes or aldehyde odors to percentages of carbon monoxide can be compared. The observations on odor were classed as "no odor of aldehydes," "slight odor of aldehydes," "distinct odor of aldehydes," and "strong odor of aldehydes."

A known quantity of formaldehyde gas was admitted into the closed room testing-chamber, and the strength of the odor was calibrated into percentages and parts per million. Although the odor of formaldehyde is not identical with that of gas fumes, it resembles the latter closely enough for this purpose. The expressions given above represent about these proportions of formaldehydes by volume:

Expression.	Formaldehydes, proportion by volume.	
	Per cent.	Parts per million.
Strong odor of aldehydes	0.01	100
Distinct odor of aldehydes	.001	10
Slight odor of aldehydes	.0005	5
No odor of aldehydes	.0005	<5

Evidently a minute quantity of aldehydes—one so very small as to be almost nondetectable by chemical means—is perceptible by the sense of smell. These observations were made during tests to determine whether any relation existed between the odor of gas fumes and the percentage of carbon monoxide present. In all, 96 determinations were made.

Of the tests in which aldehyde odors were not detected carbon monoxide was not present in three; in two tests no odor was detected although carbon monoxide (0.02 and 0.03 per cent) was present. The sample containing 0.03 per cent came from the heater using a chemical to remove noxious gases. These results tend to substantiate the conclusion that carbon monoxide is not present in dangerous quantities when aldehyde odors or gas fumes are not detectable.

When a slight odor of aldehyde was observed no carbon monoxide was found in 11 tests and 0.02 to 0.12 per cent in six tests. The highest percentage (0.12) came from a heater having a canister to remove fumes, and the two tests giving 0.10 and 0.11 per cent were of a heater of the radiant type. From these observations it is evident that a slight odor of aldehydes or gas fumes in a room in which a natural-gas heater is burning may or may not show that carbon monoxide is being produced in harmful quantities. A heater using a chemical absorbent for removing gas fumes may cause occupants of a room to feel safe when carbon monoxide is present. A slight odor from radiant heaters indicates more carbon monoxide than an odor of equal strength from other types of heaters.

In the tests where gas fumes or aldehyde odors were distinctly smelled no carbon monoxide was detected in seven tests, but 0.03 to 0.21 per cent—altogether too much for safety and health—was detected in 16 tests.

In all of the 21 tests in which the odor of aldehyde vapors was strong carbon monoxide was found in dangerous amounts—0.04 to 1.72 per cent.

From these tests the following conclusions may be made:

In a room in which a heater is burning natural gas the relation of the carbon monoxide emitted to gas fumes observed depends on the type of heater used. Heaters burning with a yellow flame and at a lower temperature may give off gas fumes, yet produce very little carbon monoxide; on the other hand, heaters burning gas at a very high temperature may give little if any odor of gas fumes and yet produce carbon monoxide. In general, with heaters that do not have a canister for removing gas fumes the absence of such fumes or aldehyde odors indicate an atmosphere in which not enough carbon monoxide is present to be dangerous to health and safety; a slight or distinct odor may or may not indicate a dangerous condition; but a strong odor is a danger sign and indicates that carbon monoxide may be present in quantities large enough to cause death in a very short time.

CONCLUSIONS.

1. The quantity of carbon monoxide that accumulated in a closed room of 1,000 cubic feet capacity, when natural-gas heaters were burned until the flames were extinguished, ranged from zero to the exceedingly dangerous concentration of 1.72 per cent.

2. In general, the liberation of carbon monoxide by natural-gas heaters may be due to one or more of several causes, such as (*a*) supplying the heaters with too much gas; (*b*) not supplying the flame with air enough for complete combustion; (*c*) faulty construction of the heaters; or (*d*) allowing the flame to impinge on metal or other surfaces so that it is chilled below the ignition point.

3. As the proportion of oxygen in the air supplied the heater diminishes, the rate of liberation of carbon monoxide remains fairly constant until the oxygen content nears the point at which the flames are extinguished: then the rate of liberation rapidly increases.

4. A free-burning flame—whether luminous, blue, or nonluminous—if supplied with an ample quantity of oxygen does not produce appreciable quantities of carbon monoxide. A "free-burning flame" is one that does not burn in contact with metal or other surfaces.

5. Lava-tip yellow-flame heaters, burning so that the flame does not come into contact with a metallic surface, do not produce carbon monoxide in appreciable quantities.

6. Heaters of this type should not be permitted to burn so that the flame touches metal surfaces. If the burner is twisted or turned so that the flame impinges on a metal surface, dangerous quantities of carbon monoxide are produced and connection to a flue becomes absolutely necessary.

7. Heaters of this type should be protected from drafts, which cause the flame to come in contact with the metal reflecting surfaces and thus give off carbon monoxide. Nor should one of these heaters be supplied with so much gas that the flames roar or extend outside the heater.

8. Heaters of the metal-inclosed blue-flame type burning under proper conditions do not produce detectable quantities of carbon monoxide. The gas flow should not be increased so that the flame extends through the holes of the inside metal grid surrounding the burner, because carbon monoxide is produced in this way.

9. Asbestos-back yellow-blue flame heaters having solid metal guards in front of the flame produce dangerous quantities of carbon monoxide and should be connected to a flue when in use. If such heaters are used without a guard the liberation of carbon monoxide is greatly reduced.

10. Radiant nonluminous-flame heaters, when operated so that the radiants glow only three-fourths of the length from the bottom to the top and when adjusted so as to entrain eight or more volumes of primary air, can be safely used without a flue in a well-ventilated room. If the heater is so operated that the radiants glow the entire length, or is so adjusted that the amount of primary air is small, it should be connected to a flue.

11. Tests of a heater provided with a canister containing a chemical to remove noxious gases did not show that the use of the canister had any appreciable effect on the liberation of carbon monoxide or carbon dioxide, but they did show that the canister removed the greater part of the "gas fumes" or "aldehyde odors."

12. Guards should not be put around a heater unless adjusted to a proper distance from the burner and provided with plenty of openings through which air may be easily drawn into the flame.

13. Heaters should be so constructed that an ample supply of secondary air is drawn into the flame to insure complete combustion.

Natural gas should not be burned in any device in which proper arrangement is not made for the admission of secondary air.

14. The most essential point in the design of the heater is to insure that the heater burns the gas completely to carbon dioxide and water vapor.

15. When a heater is connected to a flue, a large part of the heat liberated by the combustion of the gas goes up the flue and so is lost. To keep this loss to a minimum, there should be a damper in the flue; after the heater is lighted the damper should be gradually closed until the products of combustion move slowly into the flue—a matter that can be determined by watching the flame of a piece of burning paper placed near the flue or by blowing tobacco smoke into the space above the flame and noting whether the smoke is drawn into the flue or comes out into the room. Another method of saving a large part of the heat usually lost up the chimney is to use a longer flue connection with several bends in it, and thus enable the hot gases from the flame to liberate much of their heat into the room before they reach the chimney.

16. Gas fumes or aldehyde odors in a room in which a natural-gas heater is burning may or may not indicate the presence of carbon monoxide. Heaters burning with a yellow flame and at a lower temperature may liberate gas fumes but produce very little carbon monoxide; on the other hand, heaters burning gas at a high temperature may give off very slight odors and yet liberate carbon monoxide. Tests showed that when the gas fumes were not detectable by smell carbon monoxide was not given off in quantities dangerous to health and safety; a slight or distinct odor may indicate danger with one type of heater and not with another. A strong odor is evidence that enough carbon monoxide may be present to cause death in a very short time.

17. A natural-gas heater should never be used in a room in which a person is sleeping unless the heater is connected to a flue or one or more windows are open.

PUBLICATIONS ON THE UTILIZATION OF NATURAL GAS.

A limited supply of the following publications of the Bureau of Mines has been printed for free distribution. Requests for all publications can not be granted, and applicants are requested to limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines.

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PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION.

TECHNICAL PAPER 38. Wastes in the production and utilization of natural gas, and methods for their prevention, by Ralph Arnold and F. G. Clapp. 1913. 29 pp.

TECHNICAL PAPER 185. Use of the interferometer in gas analysis, by F. M. Seibert and W. C. Harpster. 1918. 18 pp., 1 pl., 6 figs.

TECHNICAL PAPER 209. Traps for saving gas at oil wells, by W. R. Hamilton. 1919. 34 pp., 3 pls., 16 figs.

TECHNICAL PAPER 253. Effects of gasoline removal on the heating value of natural gas, by D. B. Dow. 1920. 23 pp., 2 figs.

TECHNICAL PAPER 255. Chlorination of natural gas, by G. W. Jones, V. C. Allison, and M. W. Meighan. 1921. 44 pp., 9 figs.

TECHNICAL PAPER 257. Waste and correct use of natural gas in the home, by Samuel S. Wyer. 1920. 23 pp., 7 figs.

PUBLICATIONS THAT MAY BE OBTAINED ONLY THROUGH THE SUPERINTENDENT OF DOCUMENTS.

BULLETIN 120. Extraction of gasoline from natural gas by absorption methods, by G. A. Burrell, P. M. Biddison, and G. G. Oberfell. 1917. 71 pp., 2 pls., 15 figs. 10 cents.

BULLETIN 151. Recovery of gasoline from natural gas by compression and refrigeration, by W. P. Dykema. 1918. 123 pp., 15 pls., 15 figs. 25 cents.

BULLETIN 176. Recent developments in the absorption process for recovering gasoline from natural gas, by W. P. Dykema. 1919. 90 pp., 20 pls., 30 figs. 25 cents.

TECHNICAL PAPER 87. Methods of testing natural gas for gasoline content, by G. A. Burrell and G. W. Jones. 1916. 26 pp., 7 figs. 5 cents.

TECHNICAL PAPER 104. Analysis of natural gas and illuminating by fractional distillation in a vacuum at low temperatures and pressures, by G. A. Burrell, F. M. Seibert, and I. W. Robertson. 1915. 41 pp., 7 figs. 5 cents.

TECHNICAL PAPER 109. Composition of the natural gas used in 25 cities, with a discussion of the properties of natural gas by G. A. Burrell and G. G. Oberfell. 1915. 22 pp. 5 cents.

TECHNICAL PAPER 158. Compressibility of natural gas and its constituents, with analyses of natural gas from 31 cities in the United States, by G. A. Burrell and I. W. Robertson. 1917. 16 pp., 9 figs. 5 cents.

TECHNICAL PAPER 325. Natural-gas manual for the home, by R. A. Cattell. 1922. 30 pp., 8 pls., 9 figs. 10 cents.

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